VIIRS Reflective Solar Band (RSB) Performance and Uncertainty Estimates

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- Reporting on behalf of entire VIIRS SDR Calibration/Validation team -

Suomi NPP SDR Product Review
NOAA Center for Weather and Climate Prediction (NCWCP)
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Topics

- RSB Radiometric Uncertainty
- RSB Radiometric Stability
- RSB Radiometric Uniformity
- RSB Signal-to-Noise Ratio (SNR)
- Advancements since Provisional Maturity Review
- Potential RSB Data Product Improvements & Remaining Work
- Summary

Reflectance Uncertainty Requirement

Table 4.6 - VIIRS SDR Threshold Performance Characteristics

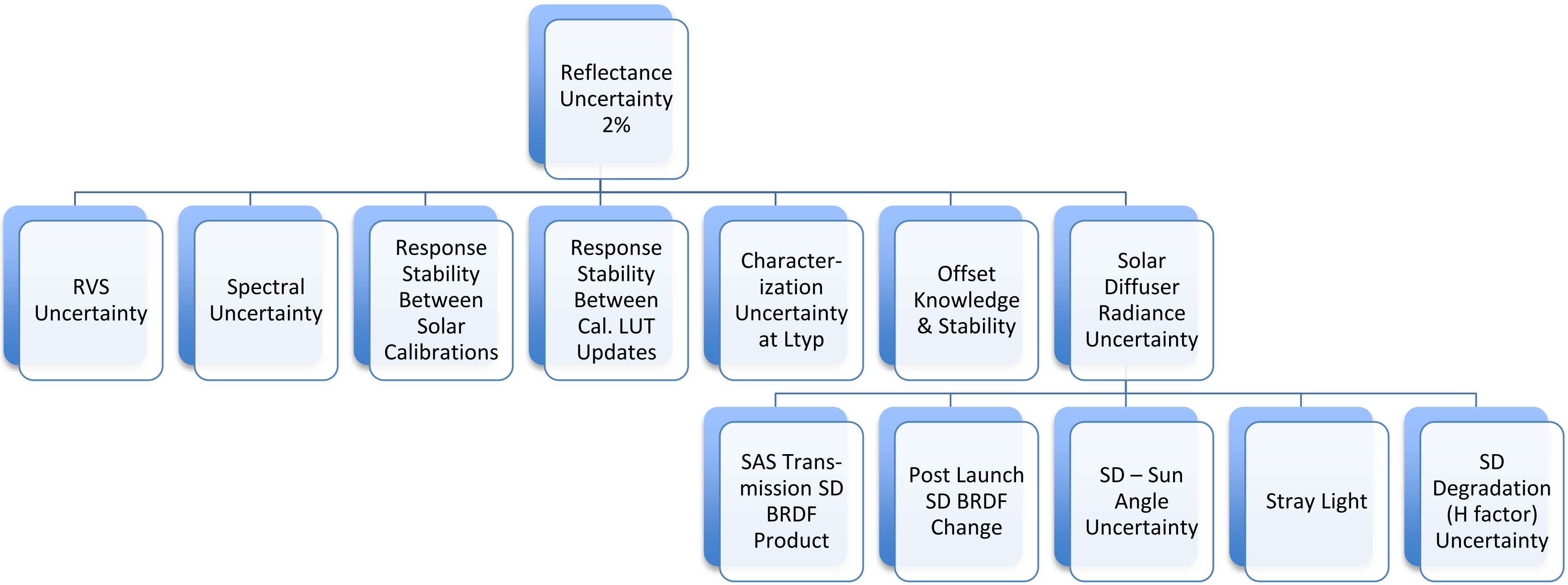
Channel	Center Wavelength (nm)	Bandpass (nm)	Maximum Polarization Sensitivity (%)	Accuracy @ Ltyp (%)	SNR @ Ltyp or NEdT @ 270 K	FOV @ Nadir (km)	FOV @ Edge-of-Scan (km)	Ltyp [(K or W/(m^2-sr-μm)]	Dynamic Range [K or W/(m^2-sr-μm)]
1	412	20	3	2	352 316	0.8	1.6	44.9 155	30-615
2	445	18	2.50	2	380 409	0.8	1.6	40 146	26-687
3	488	20	2.50	2	416 414	0.8	1.6	32 123	22-702
4	555	20	2.50	2	362 315	0.8	1.6	21 90	12-667
5	672	20	2.50	2	242 360	0.8	1.6	10 68	9-651
6	746	15	2.50	2	199	0.8	1.6	9.6	5.3-41.0
7	865	39	3	2	215 340	0.8	1.6	6.4 33.4	3.4-349
8	1240	20	NS	2	74	0.8	1.6	5.4	3.5-164.9
9	1378	15	NS	2	83	0.8	1.6	6	0.6-77.1
10	1610	60	NS	2	342	0.8	1.6	7.3	1.2-71.2
11	2250	50	NS	2	10	0.8	1.6	0.12	0.12-31.8
12	3700	180	NS	0.70	0.396	0.8	1.6	270 K	230-353 K
13	4050	155	NS	0.70	0.107 0.423	0.8	1.6	300 K 380 K	210-634 K
14	8550	300	NS	0.60	0.091	0.8	1.6	270 K	190-336 K
15	10763	1000	NS	0.40	0.07	0.8	1.6	300 K	190-343 K
16	12013	950	NS	0.40	0.072	0.8	1.6	270 K	190-340 K
17	700	400	NS	5/10/30 (2)	6	0.8	0.8	$3E^{-5}$ (1)	$3E^{-5}$ to 200 (1)
18	640	80	2.5	2	119	0.4	0.8	22	5-71.8
19	865	39	3	2	150	0.4	0.8	25	10.3-349
20	1610	60	NS	2	6	0.4	0.8	7.3	1.2-72.5
21	3740	380	NS	5	2.5	0.4	0.8	270K	210-353 K
22	11450	1900	NS	3	1.5	0.4	0.8	270K	190-340 K

v2.4, 12/13/12

Notes:
1. DNB Units are in W/(sr-cm^2)
2. DNB Low Gain / Mid-Gain / High Gain requirements
3. Dual entries indicate requirements for dual-gain channels
4. Ltyp = Typical Radiance SNR = Signal-to-Noise Ratio NS = Not Specified

- VIIRS SDR reflectance uncertainty requirement defined in LIRDS-2290, Table 4.6, JPSS Level 1 Requirements, Supplement – Final, Version 2.9, June 27,2013
- 2% reflectance uncertainty at Ltyp for all RSB except DNB

RSB Reflectance Uncertainty Tree



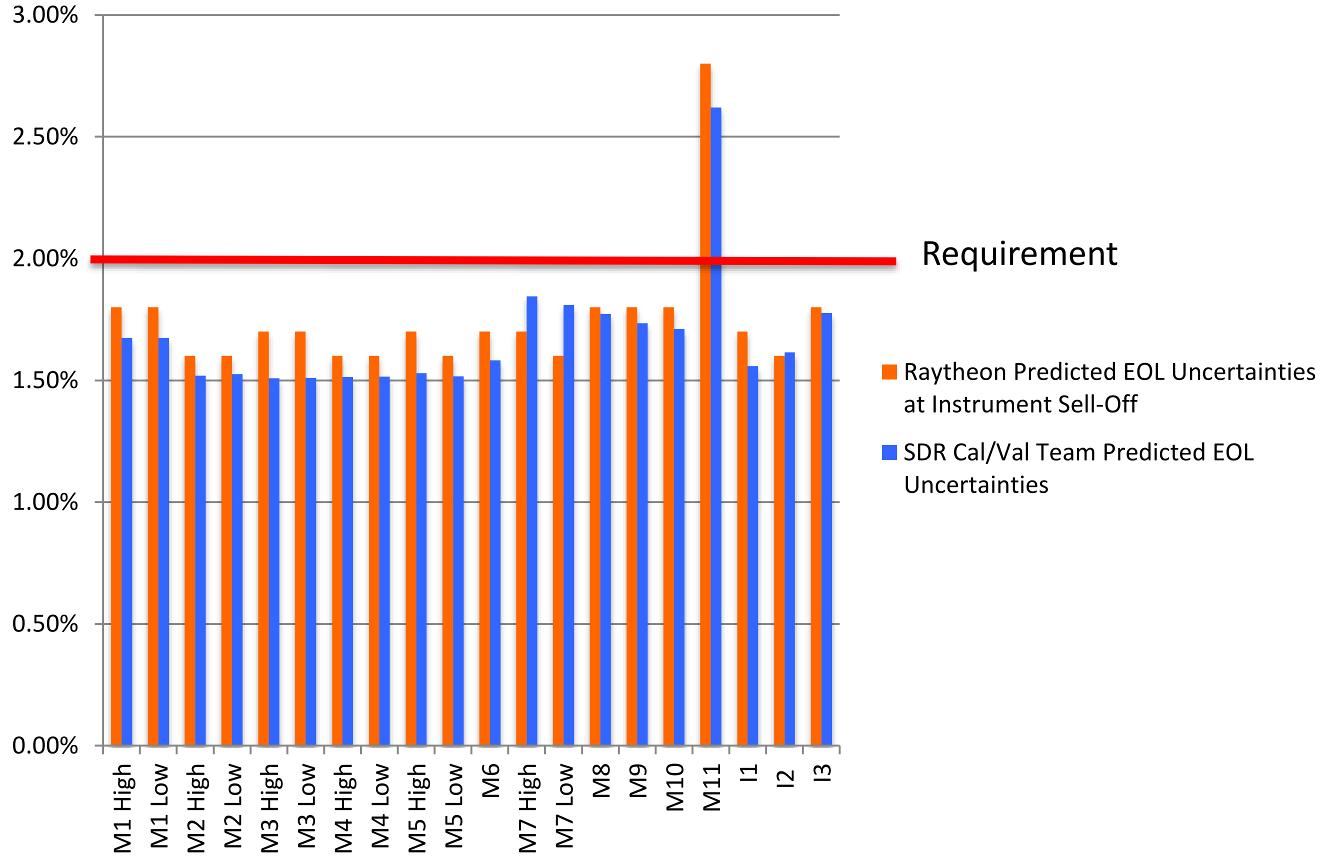
- Uncertainty tree based on Raytheon "Performance Verification Report – VIIRS FU1 Reflective Band Calibration (PVP Section 4.2.2)", 12/16/09
- Added contribution for response stability between calibration scale factor look-up table (LUT) updates (to be eliminated by automated calibration)
- Modified structure to account for LUT structural changes during cal/val

Reflectance Uncertainty Roll-Up

Error Source - Level 1	Error Source - Level 2	M1 High	M1 Low	M2 High	M2 Low	M3 High	M3 Low	M4 High	M4 Low	M5 High	M5 Low	M6	M7 High	M7 Low	M8	M9	M10	M11	I1	I2	I3
RVS Uncertainty		0.702	0.702	0.245	0.245	0.05	0.05	0.05	0.05	0.078	0.078	0.057	0.05	0.05	0.067	0.197	0.073	0.045	0.072	0.05	0.073
Spectral Uncertainty		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Response Stability Between Solar Calibrations		0.18	0.18	0.09	0.09	0.06	0.06	0.07	0.07	0.08	0.08	0.06	0.1	0.1	0.14	0.15	0.16	0.13	0.07	0.09	0.19
Response Stability Between LUT Updates		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Characterization Uncertainty at Ltyp		0.03	0.06	0.09	0.17	0.2	0.21	0.18	0.19	0.27	0.19	0.44	0.38	0.12	0.28	0.19	0.08	1.43	0.22	0.11	0.11
Offset Knowledge and Stability		0.04	0	0.04	0	0.03	0	0.03	0	0.06	0	0.05	0.02	0	0.18	0.13	0.16	1.36	0.31	0.2	0.19
Solar Diffuser Radiance Uncertainty		1.508	1.508	1.493	1.493	1.493	1.493	1.501	1.501	1.501	1.501	1.516	1.802	1.802	1.735	1.701	1.693	1.718	1.508	1.595	1.751
	SAS transmission - SD BRDF Product	1.17	1.17	1.15	1.15	1.15	1.15	1.16	1.16	1.16	1.16	1.18	1.53	1.53	1.45	1.41	1.4	1.43	1.17	1.28	1.47
	Post-Launch BRDF Change	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	SD-Sun Angle Unc.	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098
	Stray Light	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
	SD Degradation Unc.	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
RSS Total Uncertainty		**1.677**	**1.677**	**1.522**	**1.528**	**1.512**	**1.513**	**1.518**	**1.518**	**1.533**	**1.52**	**1.585**	**1.848**	**1.812**	**1.776**	**1.738**	**1.714**	**2.622**	**1.562**	**1.618**	**1.78**

- Values highlighted in yellow have been updated based on changes during cal/val
  - Updated screen transmission and SD BRDF LUTs
  - Predict-ahead errors in weekly calibration scale factor updates
- Non-compliance in M11 consistent with status at instrument sell-off
  - Ltyp coincides with Lmin, very far from solar calibration tie point

Predicted EOL Reflectance Uncertainties



- Slight improvement in EOL predictions for most bands
- However, differences in EOL predictions are likely within uncertainties in the uncertainty analysis itself

Radiometric Stability Requirement

TBR-2	L1RDS-92	**Resolve:** The system shall maintain the mean calibrated radiometric retrieved value of an SDR or TDR for a uniform scene to a relative accuracy of 2% (TBR-2).	JPSS PSE	Defer until S-NPP SDRs achieve Validation maturity to confirm no unintended system impacts	8/31/2013
TBR-3	L1RDS-14	**Resolve:** The mean calibrated radiometric response of each channel of an instrument to a uniform scene shall not change by more than +/- 1% (TBR-3) for all spectral channels over time scales longer than two weeks up to and including the sensor design life.	JPSS PSE	Defer until S-NPP SDRs achieve Validation maturity to confirm no unintended system impacts	8/31/2013

- LIRDS-14 is allocated to the Flight System
- Augmentation of LIRDS-2290 will replace LIRDS-92
  - Per-band calibration stability requirements will be added to Table 4.6
  - Resolution of TBRs to be informed by understanding of calibration stability achieved at Validated SDR maturity
- VIIRS SDR Cal/Val team has been working to a calibration stability “target” of 0.1%
  - Driven principally by OCC EDR need for stringent calibration uniformity (10x magnification of SDR errors is typical)

Radiometric Stability Uncertainty Tree

Radiometric Stability

TBS Time Scales

TBS Magnitudes

Response Stability Between Solar Calibrations

Time Scale: 1 orbit

~ 0.1% - 0.2%

Calibration Scale Factor Cyclic Variation

Time Scale: 1.7 weeks

~ 0.1% VNIR only

Calibration Scale Factor Cyclic Variation

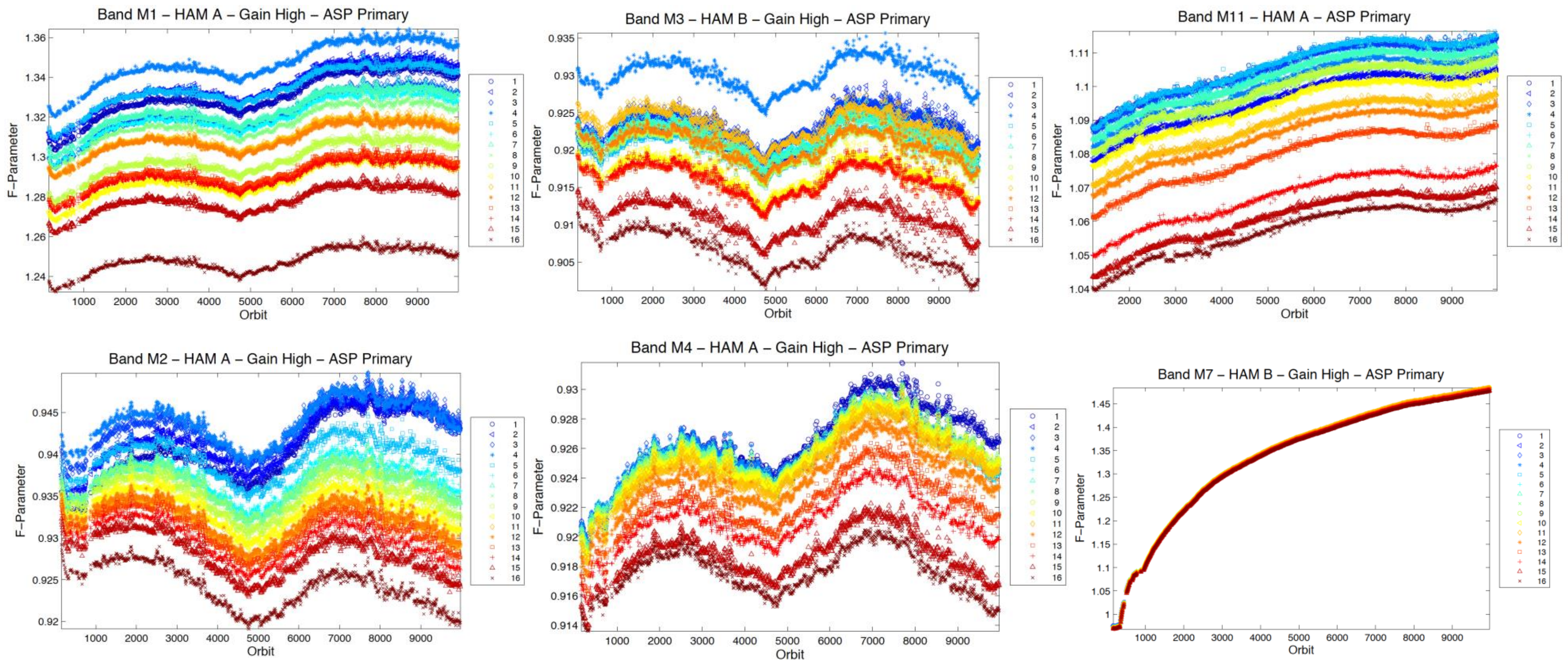
Time Scale: 1 year

~ 0.5% VNIR

~ 0.1% M11

- Predict-ahead calibration errors assumed removed by RSBAutoCal
- “Response Stability Between Solar Calibrations” from Raytheon PVR
- Observed temporally cyclic variations in calibration scale factor (F) time series indicate radiometric error
  - F = Calculated SD radiance/Measured SD radiance

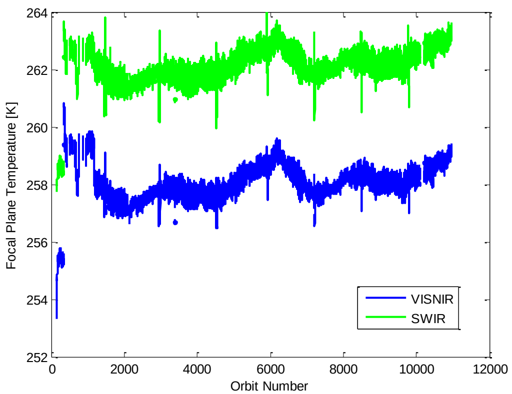
Annual Cycle in F Factor Time Series



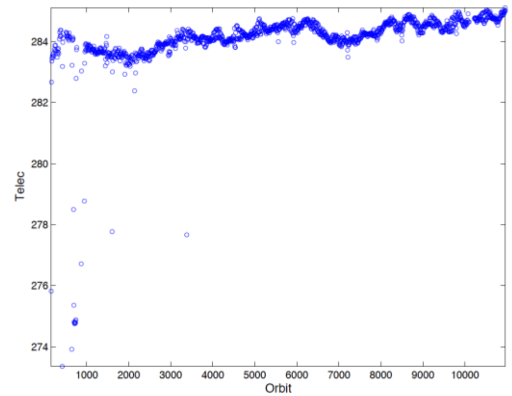
- Two years of per-orbit F factors shown for M1-M4, M11, M7
- Variations similar across detectors, bands, gain states, where observable
- Not observable in bands dominated by RTA degradation impact, e.g., M7
- Most likely due to error in calibration coefficient temperature dependence and/or SAS transmission – SD BRDF LUT such that calculated SD radiance does not faithfully track measured SD radiance
  - VisNIR FPA and SWIR FPA temperatures have annual cycle
  - Solar geometry (azimuth, declination) has annual cycle

Annual Cycles in Inputs to F Factors

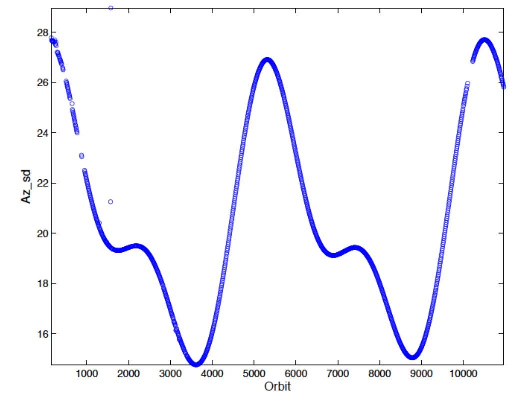
VisNIR FPA & OMM Temperatures



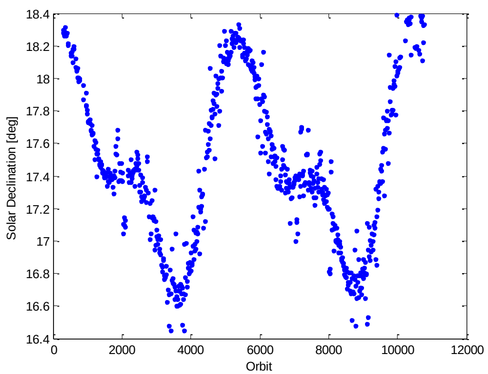
Electronics Temperature



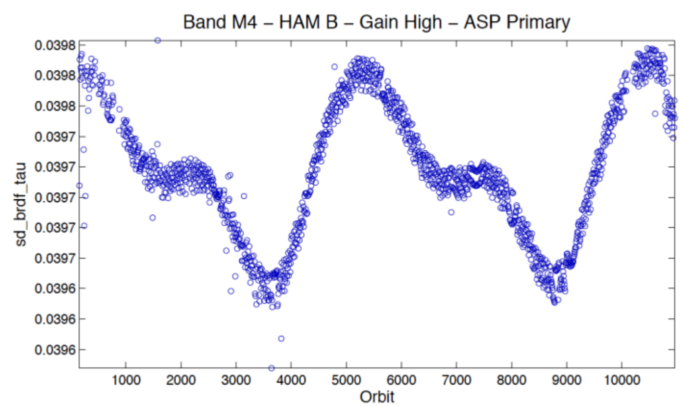
Solar Azimuth



Solar Declination

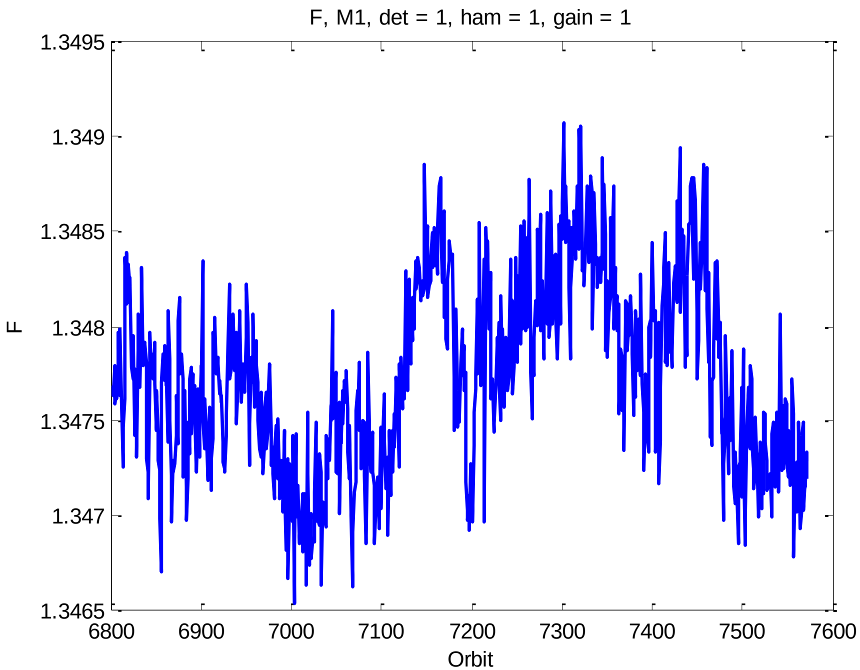


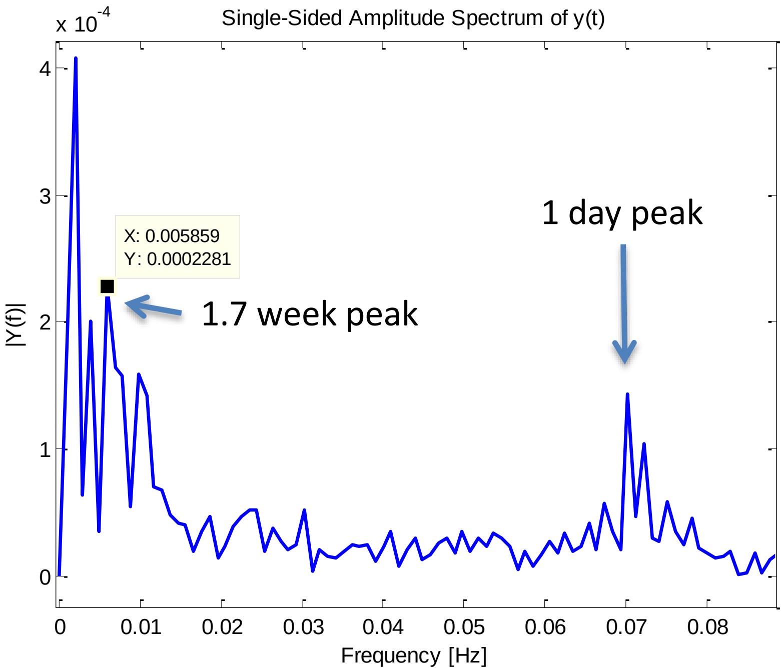
SAS Screen Transmission – SD BRDF Product LUT Values used in M4 HG F Factors



- Cycles in FPA temperature propagate to cycles in calibration coefficients used in F factor calculation
- Cycles in solar azimuth and declination propagate to cycles in values drawn from SAS Screen Transmission – SD BRDF Product LUT for use in F factor calculation

1.7 Week Cycle in F Factor Time Series





- All VisNIR bands except those most heavily impacted by RTA degradation exhibit "ripple" in F factor time series with period of approximately 1.7 weeks (170 orbits) and roughly 0.1% magnitude
- Ripple not entirely regular but similar across detectors, bands, gain states, where observable
- Portion of de-trended M1 F factor time series shown above on left was Fourier analyzed, and spectrum is shown on right
  - Peak at 0.0059 Hz corresponds to 170 orbits or 1.7 weeks
  - Smaller peak at 0.07 Hz corresponds to 14.2 orbits or 1 day and is also observable in time series superimposed on lower frequency ripple
- No physical quantity relevant to calibration having a period of 1.7 weeks has been identified as yet

Radiometric Uniformity Requirement

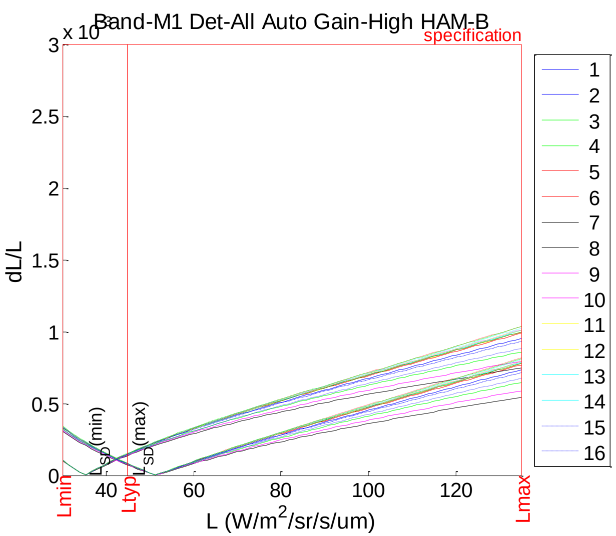
4.3.9.2.5 Relative Radiometric Response

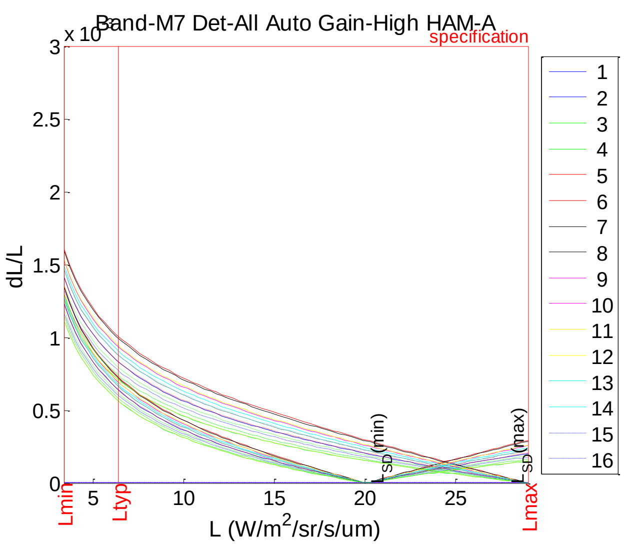
V_PRD-12759 The calibrated output of all channels within a band shall be matched to the band mean output within the NEdL / NEdT (1 sigma) when viewing a uniform scene. The matching condition shall be met between radiance levels from L_{min} to 0.9 L_{max}.

- Requirement is extremely difficult to meet, requiring roughly 0.1% uniformity at the top of the dynamic range due to VIIRS excellent NEdLs in RSB
  - "Uniformity" here means worst case deviation of detector calibration radiance from the detector mean radiance
- All low gain VisNIR bands and I1, I2, M10, M11 were predicted to fail requirement at instrument sell-off.

Radiometry Uniformity Error Sources

- Non-uniformity in radiance at Solar Diffuser (SD) tie point
  - Non-uniformity in Solar Diffuser (SD) radiance, e.g., due to retro-reflection effects
  - Estimated by instrument vendor to be ~ 0.5% of SD radiance and non-uniform, but not characterized for varying solar beam geometries
  - Averaged out somewhat by large detector footprint on SD
- Relative errors in calibration coefficients produce "fan-out" of differing calibration errors per detector, as shown below for M1 HG and M7 HG
  - Largest impacts are at extremes of measurement range
- Also: Out-of-family edge detector response, crosstalk effects, RSR band-averaging effects

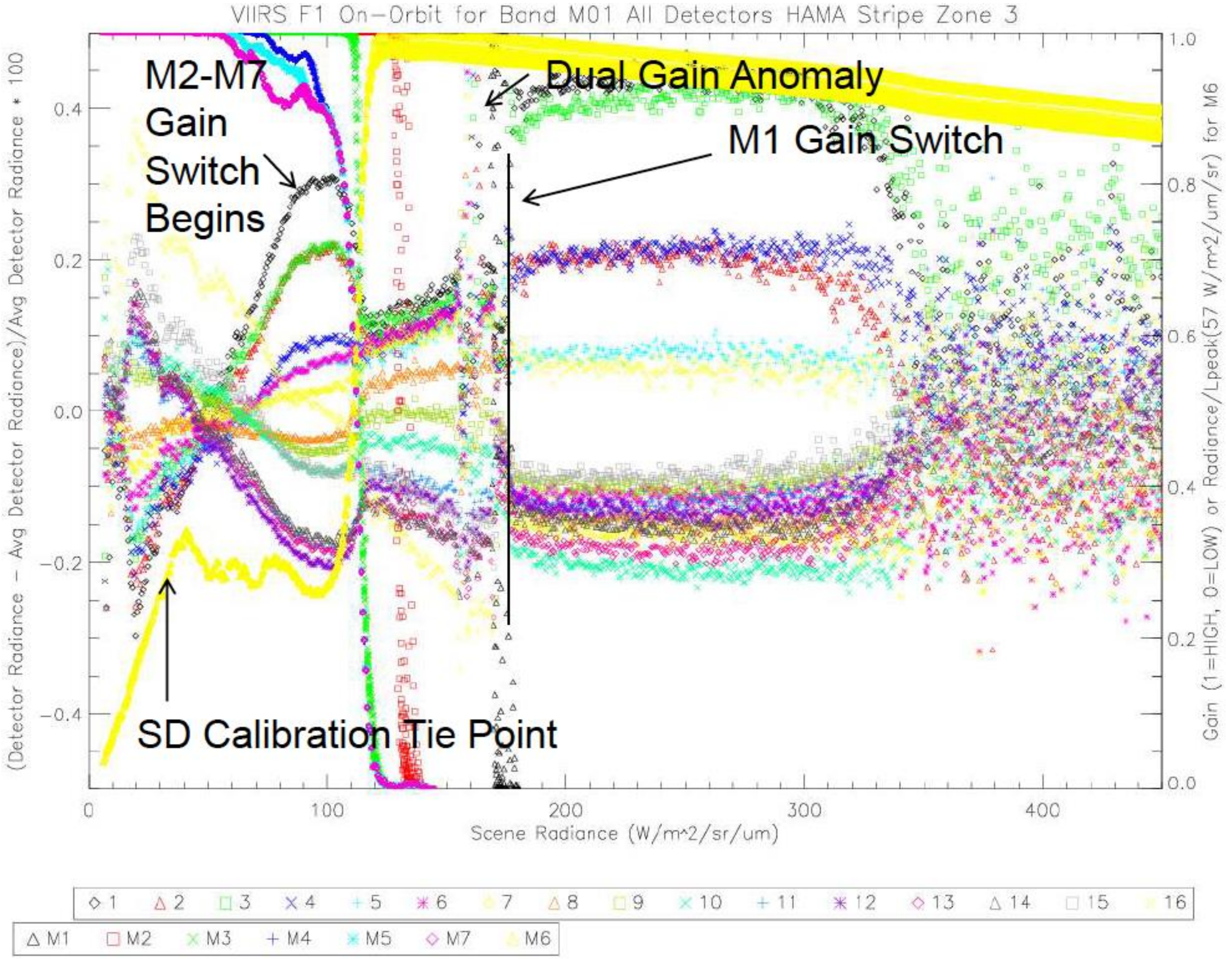




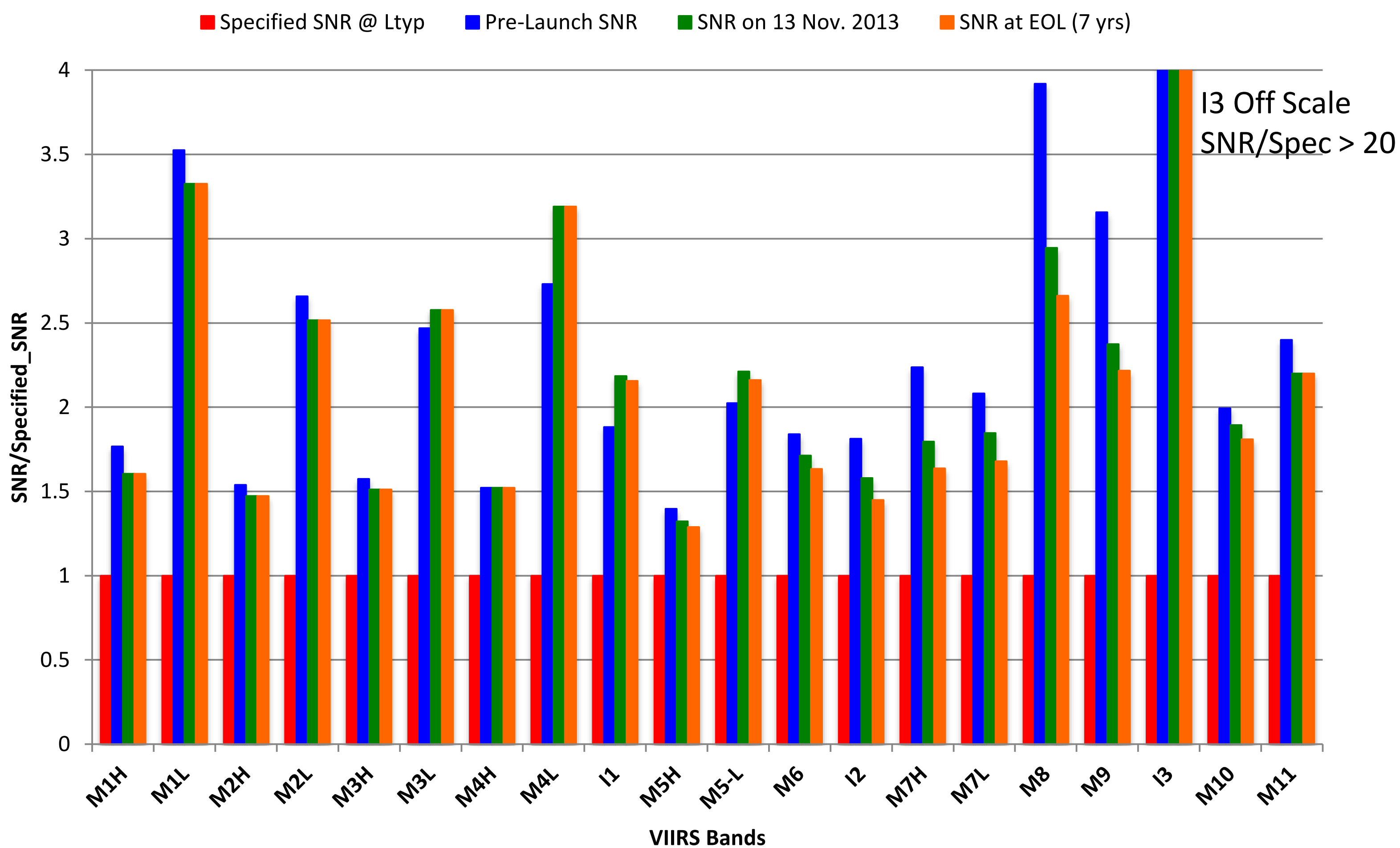
Radiometry Uniformity Characterization

- Uniform portions of scenes averaged over multiple orbits and stratified by mean radiance reveal systematic detector-dependent calibration errors, i.e., striping
- Striping behavior is extremely complex, varying with scan angle, gain state, and gain state transitions in other bands (crosstalk effects)

Band M1 HAM A striping near nadir with gain bit transitions overplotted

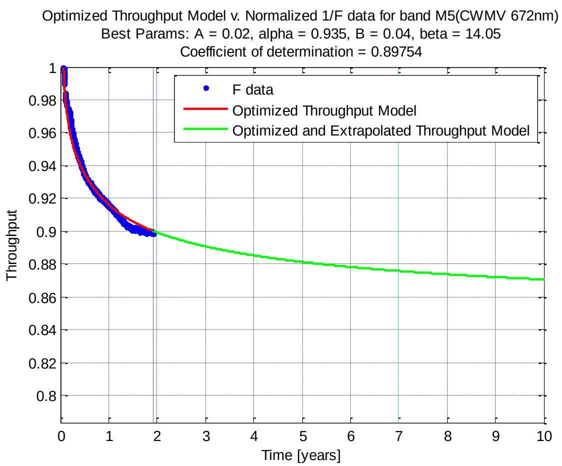


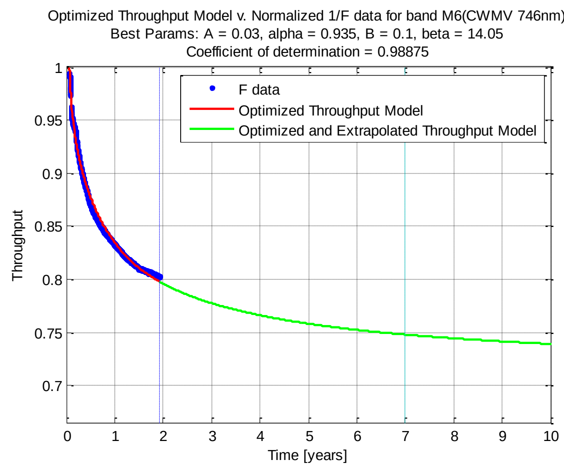
Signal-to-Noise-Ratio (SNR)

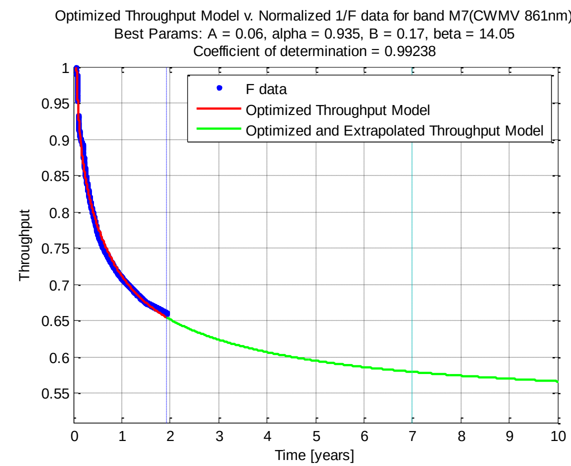


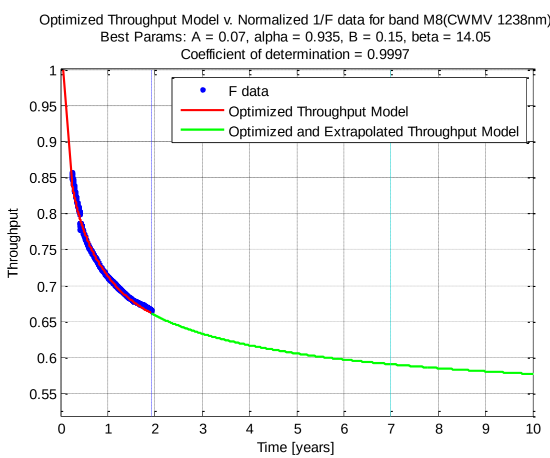
RTA Throughput Degradation

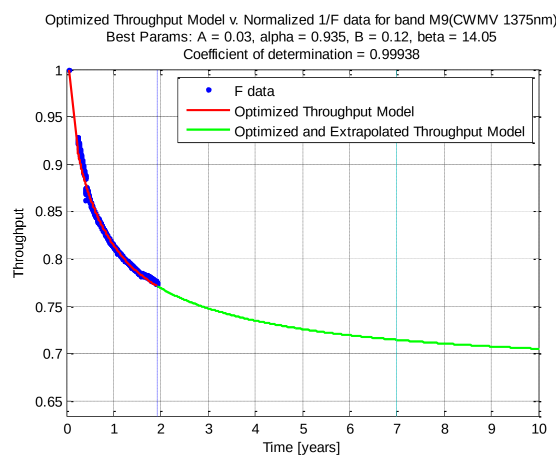
- RTA throughput degradation rate continues to slow
- Trending and extrapolations for the most affected M bands shown below

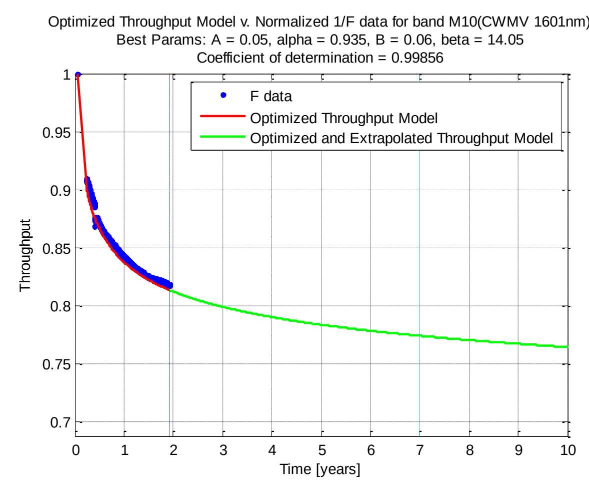












Advancements Since Provisional Maturity Review

Automated Calibration of the VIIRS Reflective Solar Bands (1)

- S-NPP VIIRS RSB are currently calibrated via updates to look-up tables (LUTs) utilized by operational ground processing in JPSS IDPS
  - 3 RSB LUTs per week and 2 Day-Night Band (DNB) LUTs per month have been provided by Aerospace operational support team since February 2012 to maintain RSB calibration
  - LUT update process allows top-level 2% calibration uncertainty requirement to be met
  - However, LUT update process injects predict-ahead calibration errors that violate 0.1% bias stability required by Ocean Color/Chlorophyll EDR

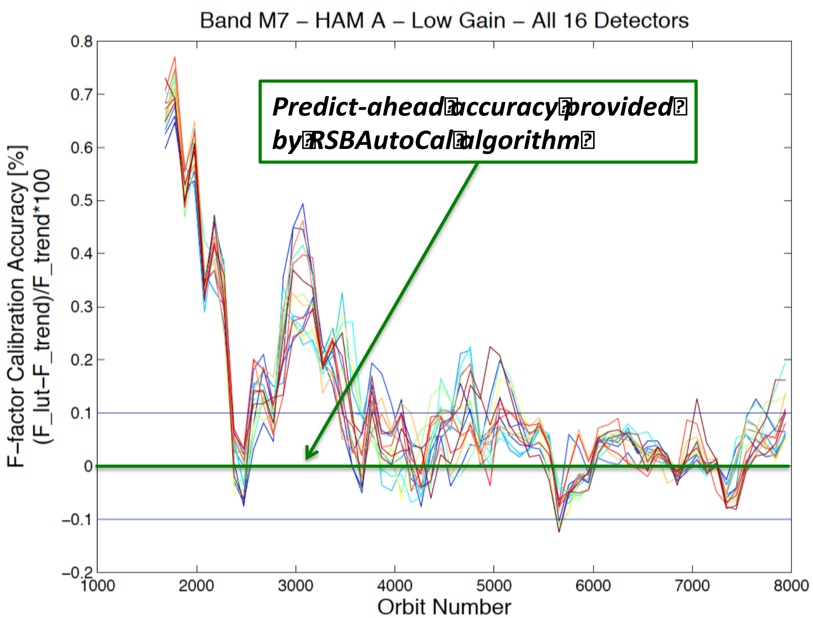
- An algorithm for automated calibration of the RSB, RSBAutoCal, has been developed by Aerospace that applies calibration scale factors to SDR products as frequently as calibration data are acquired, once per orbit
  - Predict-ahead calibration errors are eliminated
  - DNB offset drift correction from calibrator data is free of airglow contamination
  - Significant cost savings to program through elimination of almost all manual LUT updates for RSB calibration maintenance

- Aerospace delivered RSBAutoCal science code and AERB package to DPA in April 2013
  - AERB approval in May 2013
  - Operationalized and tested by Raytheon, the IDPS contractor
  - Transferred to IDPS operations in Mx8.0 code on 14 November 2013 in manual mode
  - RSBAutoCal operating normally to generate calibration parameters, which are not applied in manual mode but available for evaluation

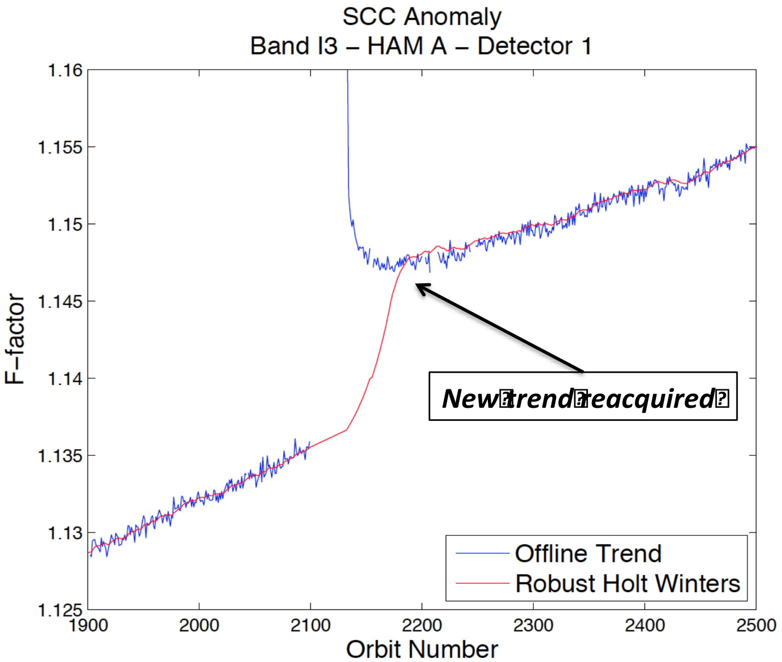
Automated Calibration of the VIIRS Reflective Solar Bands (2)

- RSBAutoCal improves SDR quality and robustness, while reducing cost

Elimination of LUT predict-ahead error significantly improves radiometric stability



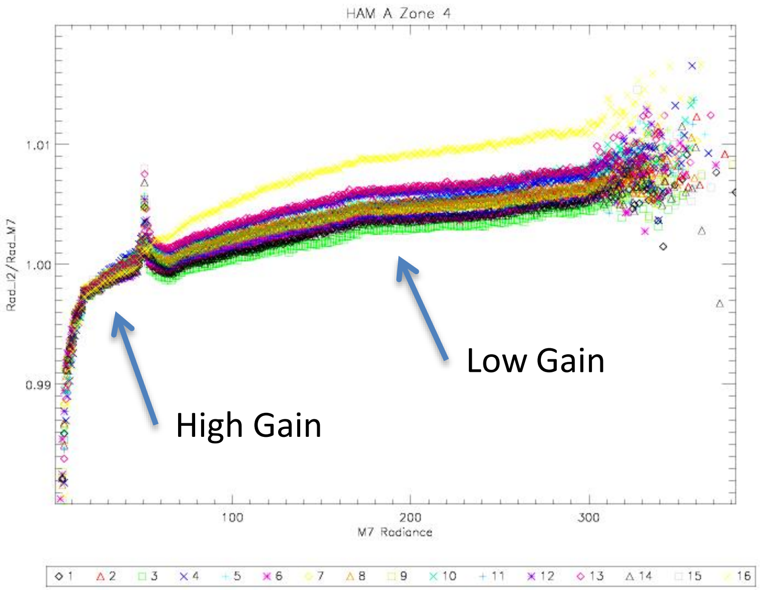
RSBAutoCal bridges data gaps in well behaved manner and rapidly recaptures trends



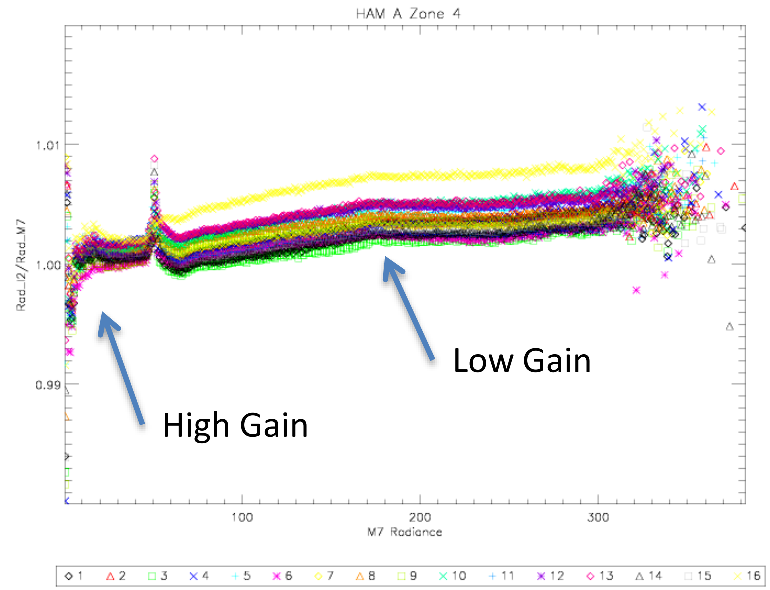
- RSBAutoCal advances the state of the art in calibrating the JPSS series of VIIRS instruments and is applicable to similar remote sensing instruments developed for other programs

Mitigation of I2/M7 Discrepancy

I2/M7 Radiance Ratio vs M7 Radiance
with Baseline Calibration Coefficients



I2/M7 Radiance Ratio vs M7 Radiance
with c0=0 c2=Refit Calibration Coefficients



- c0/c1 and c2/c1 calibration coefficient ratios were the key derived parameters from pre-launch RSB response characterization
- c0 does not arise in the derivation of the radiance retrieval equation, but is added post hoc to compensate for potential errors in other model parameters
- It was found in pre-launch data analysis that for most detectors in many RSB, c0/c1 = 0 to within 2-sigma measurement uncertainty
- c2/c1 was derived pre-launch for all bands setting c0 = 0
- Use of the c0 = 0, c2 = refit calibration coefficients substantially improves consistency between I2 and M7, as shown above
- This finding is strong evidence that the c0 = 0, c2 = refit calibration coefficients would reduce radiometric uncertainty in ALL RSB if used to update the calibration coefficient LUT, as predicted pre-launch

Potential RSB Data Product Improvements & Remaining Work

Improvements in Work or Under Investigation

- Updated screen transmission and SD BRDF related LUTs are in work
  - Provide better behaved SD degradation factor (H) time series
  - Improve radiometric uncertainty and stability
- Improved calibration coefficients with c0 = 0 constraint available and under investigation
  - Known to mitigate I2/M2 discrepancy
  - Expected to mitigate or eliminate M11 uncertainty non-compliance
  - Expected to mitigate striping
- RSBAutoCal input parameters are being tuned for optimal automated RSB calibration performance

Remaining Work

- Diagnose cause(s) of cyclic F factor behavior that degrade radiometric stability
- Develop techniques to investigate radiometric bias changes between solar calibrations (within an orbit)
- Resolve discrepancies between lunar and solar calibration analysis
  - Fold in any modifications of stability uncertainty tree based on lunar calibration trending analysis, after discrepancies are resolved
- Continue striping investigation
- Develop SDR-level uncertainty trees for realistic earth scenes, not just uniform, unpolarized test scenes
  - Quantify uncertainties due to polarization sensitivity
    - Polarization sensitivity is strongly detector dependent in VIIRS
  - Characterize effect of scene spatial structure on radiometric uncertainty particularly nearby very bright or dim regions

Summary

- IDPS RSB data products generally perform very well
- Performance will improve when calibration is fully automated
  - Greater radiometric stability
  - Robustness to data gaps and trend changes
- Additional data product improvements are in work that will enhance uncertainty, stability and uniformity performance
  - Application of c0 = 0 coefficients developed pre-launch will reduce I2/M7 discrepancy
  - Improved screen transmission and SD BRDF related LUTs
- Additional characterization needed to address remaining instrument artifacts that limit uniformity and radiometric stability
  - Striping
  - Spurious temporal modulations in calibration

Back-up Slides

Calibration Coefficient Uncertainty Impacts on Absolute Radiometric Uncertainty

- Retrieval equation provides basis for rigorous error propagation from response coefficient ratio uncertainties/correlations to on-orbit retrieved radiance uncertainty

$$\bar{L}_{EV} = \frac{RVS(\theta_{SD})}{RVS(\theta_{EV})}\bar{L}_{SD}\frac{\left(a_0 + a_1 dn_{EV} + a_2 dn_{EV}^2\right)}{\left(a_0' + a_1' dn_{SD} + a_2' dn_{SD}^2\right)}$$

Sensitivity of scale to instrument temperture from RC-3 test

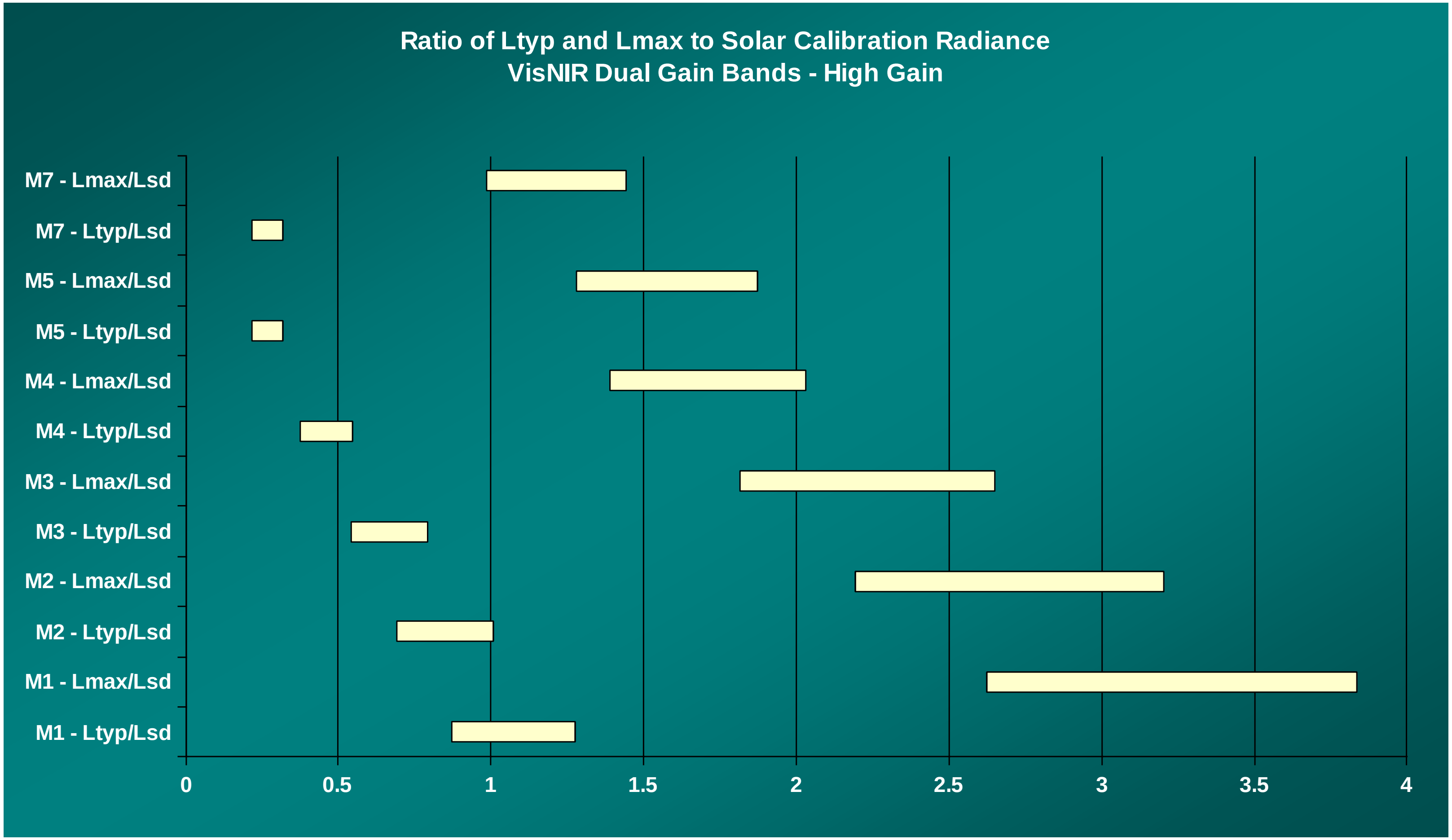
Scale from solar cal

$$= \frac{RVS(\theta_{SD})}{RVS(\theta_{EV})}\left(\frac{\bar{L}_{SD}}{\frac{a_0'}{a_1'} + dn_{SD} + \frac{a_2'}{a_1'} dn_{SD}^2}\right)\left(\frac{a_1}{a_1'}\right)\left(\frac{a_0}{a_1} + dn_{EV} + \frac{a_2}{a_1} dn_{EV}^2\right)$$

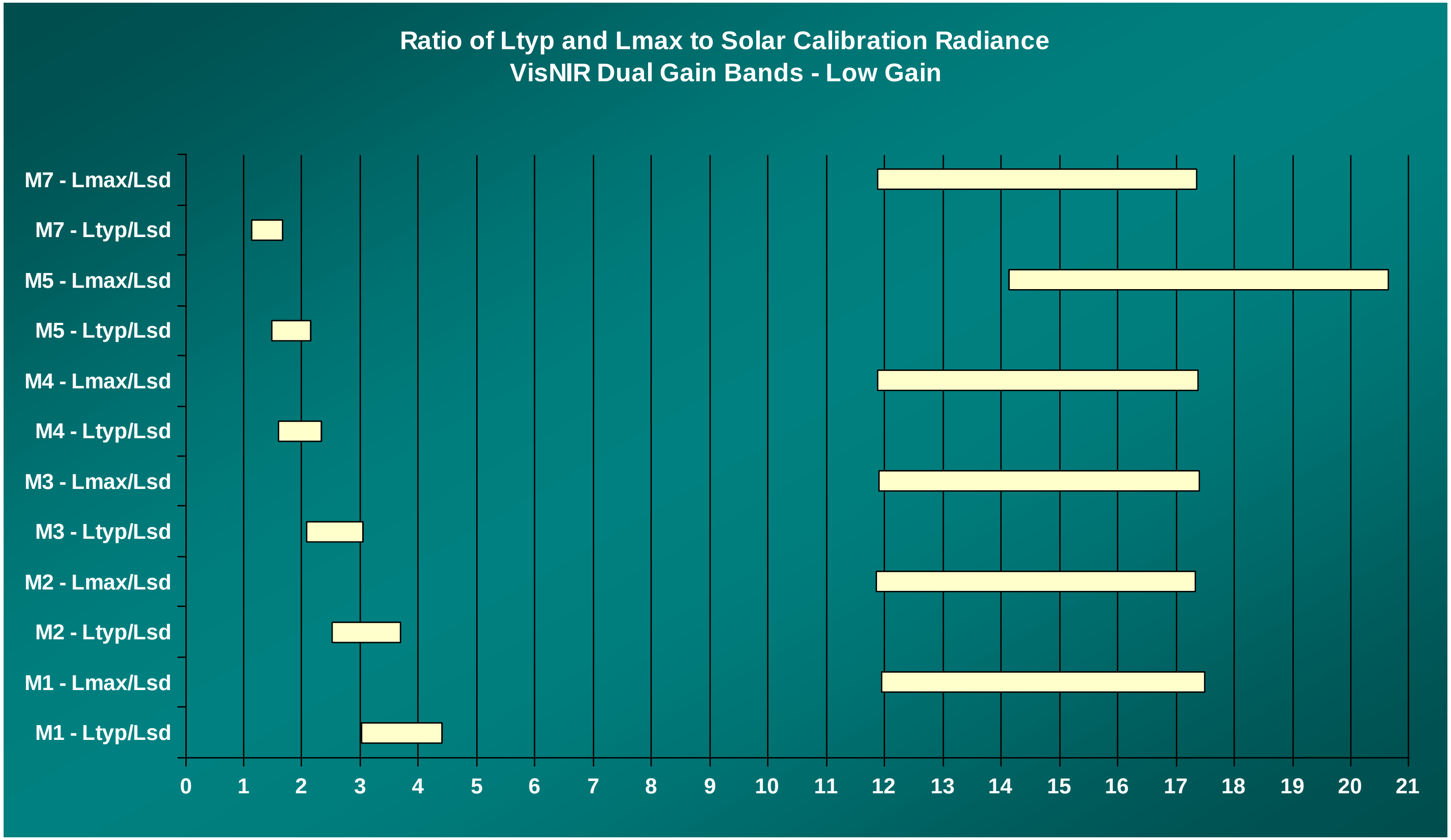
Earth scene contribution

- Minimal required characterizations from test program follow immediately from retrieval equation
  - Response coefficient ratios and their uncertainties and correlations
    - Based on RC-2
  - Functional dependence of response coefficients on thermal state (e.g., T_{FPA} and T_{ASP}), if needed to meet requirements, and associated uncertainties in parameters determining functional form
    - Based on RC-3
- Radiance retrieval uncertainty due to uncertainties in response coefficients increases as separation between earth view and solar calibration radiances increase

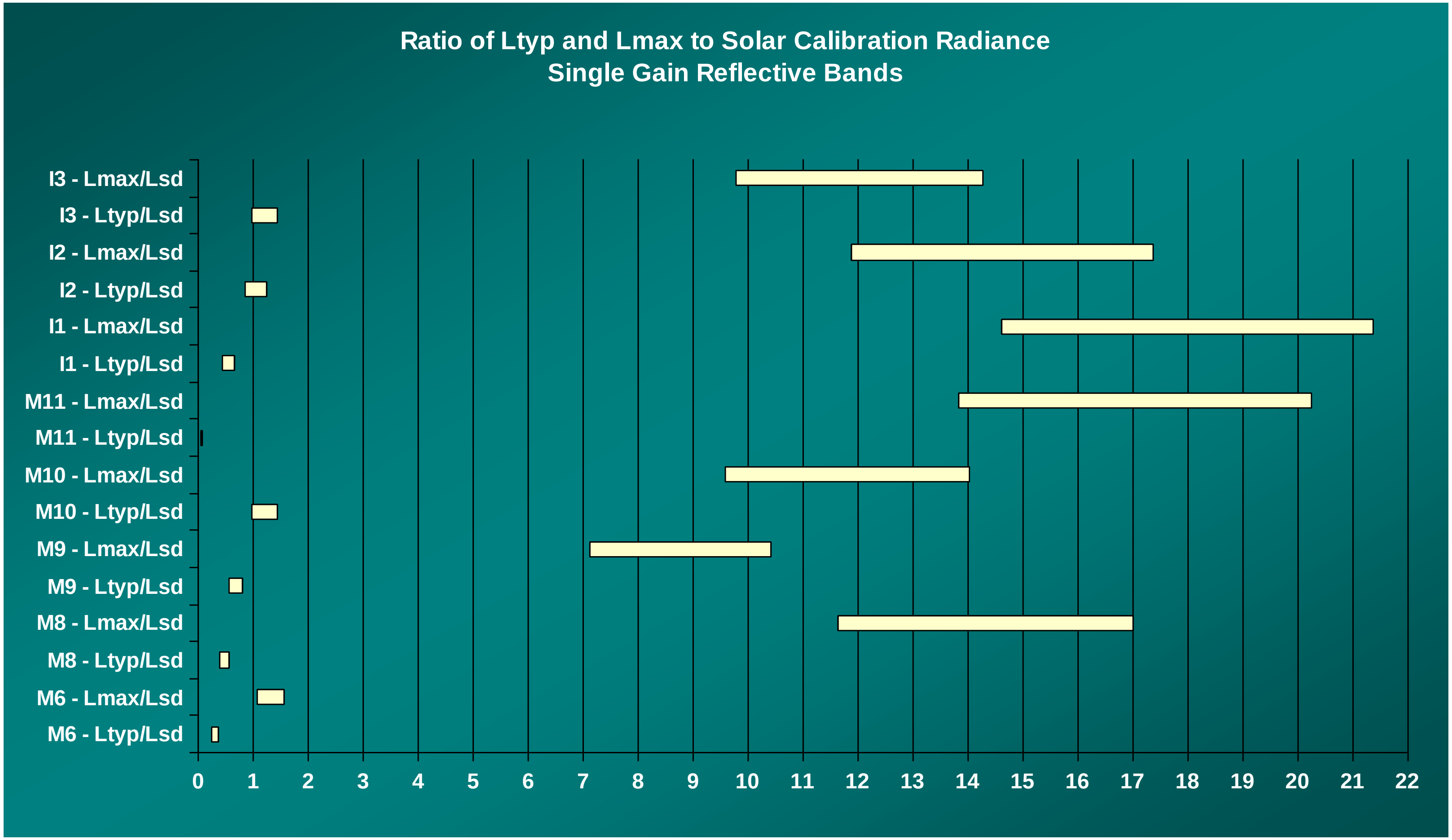
Ratio of Typical and Maximum Radiance to Solar Diffuser Radiance – VisNIR, High Gain



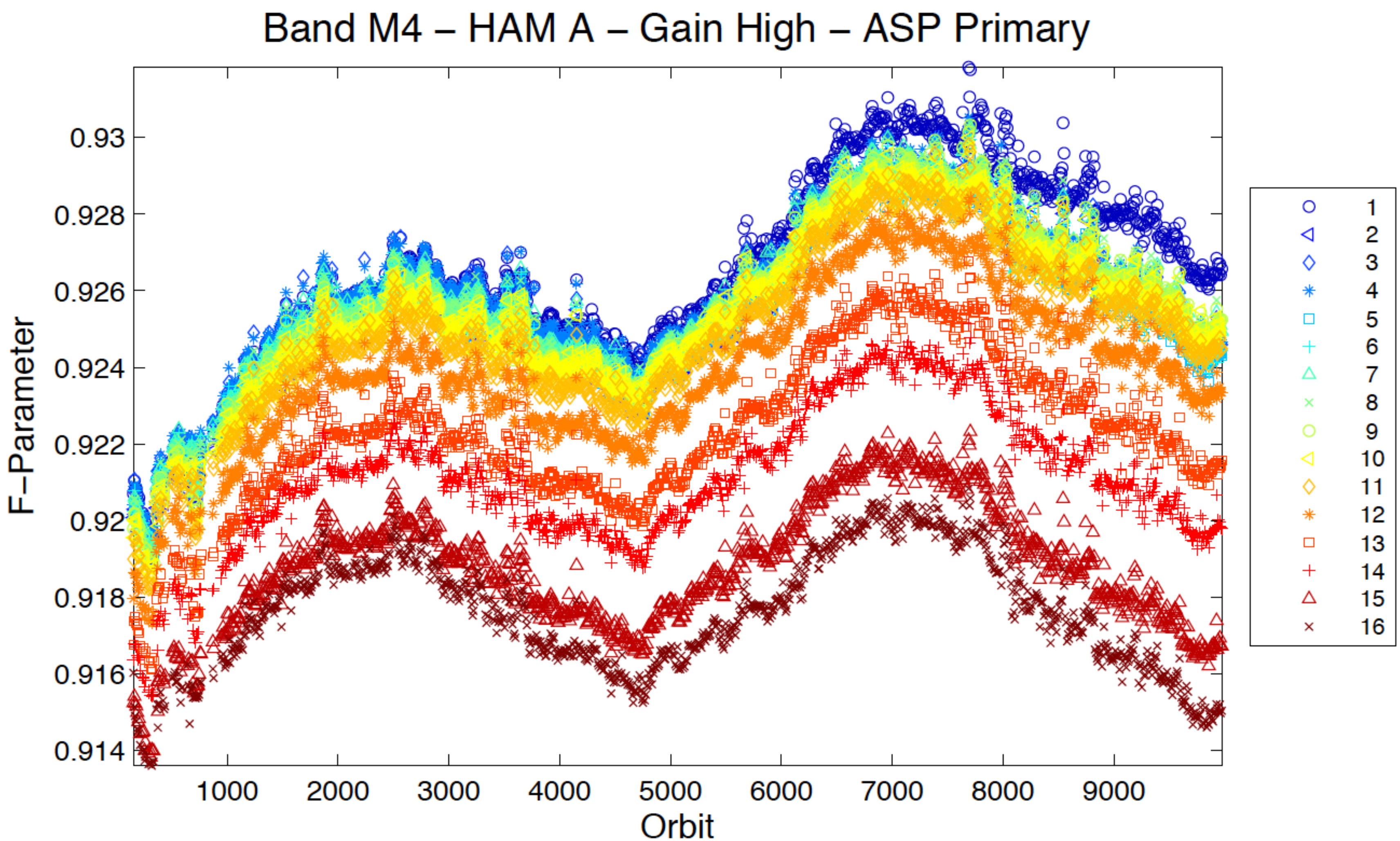
Ratio of Typical and Maximum Radiance to Solar Diffuser Radiance – VisNIR, Low Gain



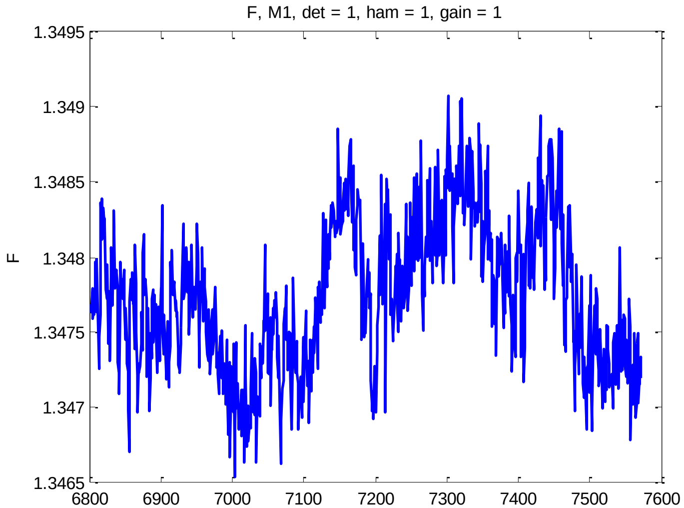
Ratio of Typical and Maximum Radiance to Solar Diffuser Radiance – Single Gain RSB

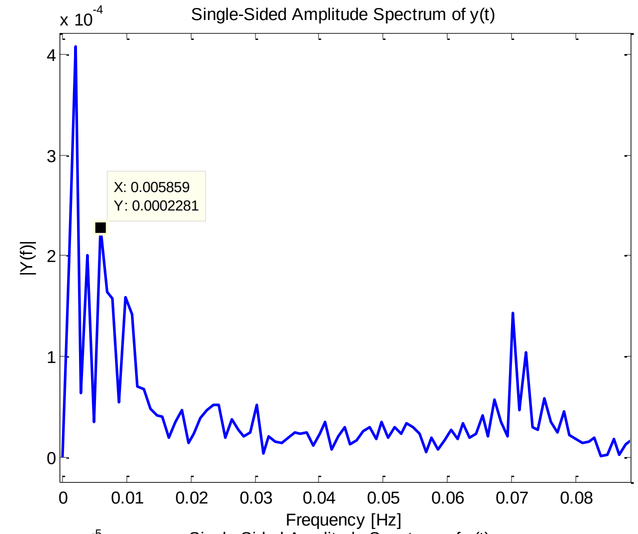


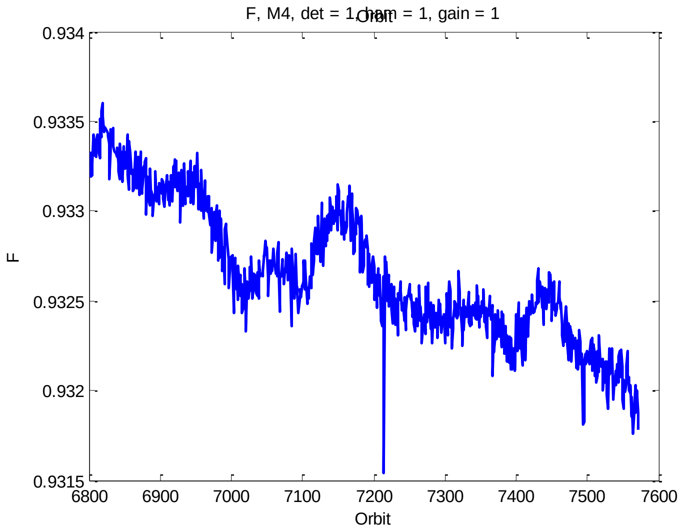
Annual Cycle in M4 HG F Factors

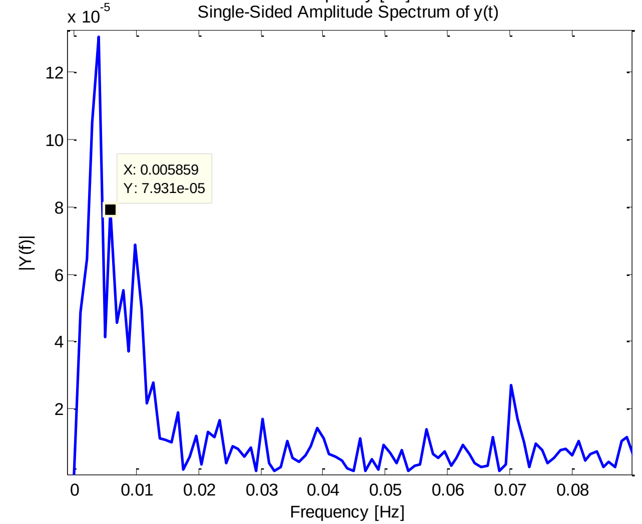


1.7 Week Cycle in F Factor Time Series
M1 & M4



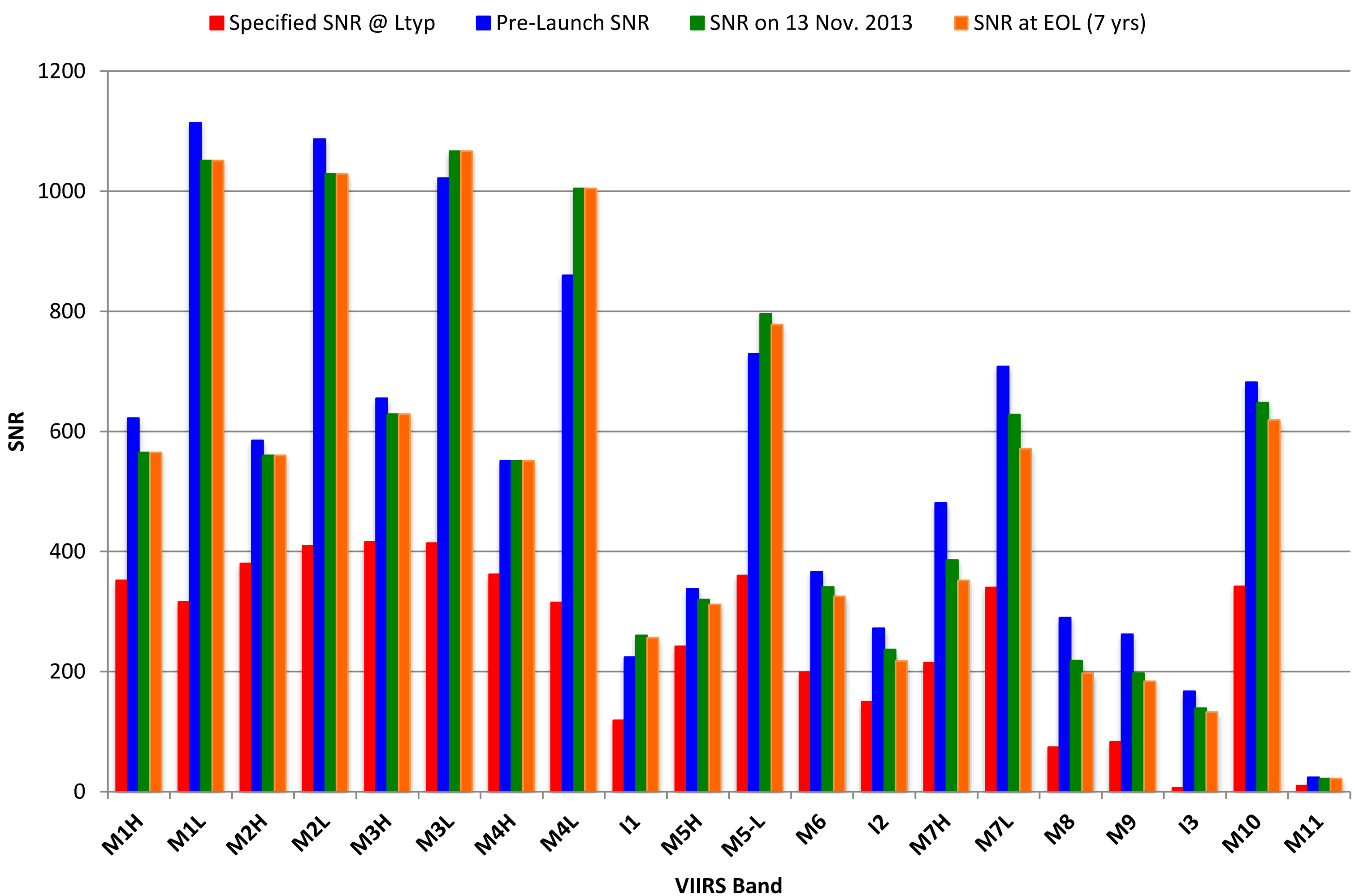






- M1 and M4 time series show similar temporal variations, although the behaviors are not highly regular in either band
- FFT show same local peak associated with 1.7 week cycle, but part of cluster of local peaks suggesting perhaps a superposition of effects on this time scale

Signal-to-Noise Ratio (SNR)



RTA Throughput Degradation – I Bands